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A SUB-SCALE TURBOJET TEST CELL
FOR DESIGN EVALUATIONS AND ANALYTICAL
MODEL VALIDATION

BY

H. W. HEWLETT, P. J. HICKEY, D. W. NETZER

SEPTEMBER 1977

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Prepared for:
Naval Air Propulsion Test CEnter
Trenton, NJ 09628

NAVAL POSTGRADUATE SCHOOL

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The work reported herein was supported by the Naval Air Propulsion Center, Trenton, NJ, as part of the Naval Environmental Protection Technology Program.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER (14) NPS-67Nt77091 ✓	2. GOVT ACCESSION NO. / 3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) A SUB-SCALE TURBOJET TEST CELL FOR DESIGN EVALUATIONS AND ANALYTICAL MODEL VALIDATION,	5. TYPE OF REPORT & PERIOD COVERED (9) Interim rept.
7. AUTHOR(S) (10) Holden [redacted] W./ Hewlett P. J./Hickey David [redacted] W./Netzer	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School ✓ Monterey, CA 93940	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS N623765WR00037
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Air Propulsion Test Center Trenton, NJ 09628	12. REPORT DATE (11) Sep[redacted]77 / 13. NUMBER OF PAGES ~~96~~ (12) 346 p.
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASSIFIED / 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Turbojet Test cell

(cont fr p. 5)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A 1/8 scale turbojet test cell has been designed and constructed. The test cell is to be employed for evaluation of optimum augmentor design and pollution abatement methods and for validation of analytical models. Initial evaluation of the test cell demonstrated its versatility and ease of operation as well as some deficiencies. Model operating characteristics and planned investigations are discussed.

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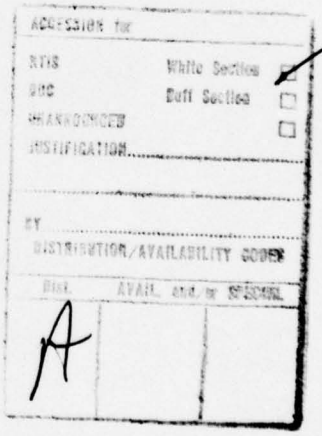
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TABLE OF CONTENTS

Section		Page
I.	INTRODUCTION	4
II.	METHOD OF INVESTIGATION	8
III.	EXPERIMENTAL APPARATUS	9
	A. DESIGN METHODOLOGY	9
	B. DESCRIPTION OF APPARATUS	10
IV.	INITIAL SYSTEM EVALUATION	14
V.	SYSTEM MODIFICATIONS	18
VI.	SUMMARY OF CURRENT INVESTIGATIONS	19
VII.	REFERENCES	22
	INITIAL DISTRIBUTION	44



LIST OF TABLES

I. COMPARISON OF EXPERIMENTAL DATA TO ANALYTICAL MODEL PREDICTION 16

II. SYSTEM DEFICIENCIES AND IMPLEMENTED MODIFICATIONS. . . . 18

III. AUGMENTOR DESIGN STUDY 20

IV. SUMMARY OF MEASURED PARAMETERS FOR MODEL VALIDATION . . 21

LIST OF FIGURES

1. SCHEMATIC OF TYPICAL TURBOJET TEST CELL 23
2. PHOTOGRAPH OF 12-STAGE ALLIS CHALMERS AXIAL COMPRESSOR . . 24
3. SCHEMATIC OF RAMJET ENGINE 25
4. PHOTO OF RAMJET WITHOUT BYPASS AIR SHROUD 26
5. PHOTO OF RAMJET ASSEMBLY 26
6. SCHEMATIC OF INITIAL 1/8 SCALE TURBOJET TEST CELL 27
7. PHOTOGRAPH OF INITIAL 1/8 SCALE TURBOJET TEST CELL 28
8. PHOTOGRAPH OF INITIAL 1/8 SCALE TURBOJET TEST CELL - TEST SECTION 29
9. CAVITATING VENTURI, PRESSURE VS. FLOW RATE 30
10. DATA SENSOR LOCATIONS ON THE 1/8 SCALE FACILITY 31
11. SCHEMATIC DIAGRAM OF DATA REDUCTION SYSTEM UTILIZING THE HEWLETT-PACKARD 9830 A CALCULATOR 32
12. TYPICAL INLET VELOCITY PROFILE OBTAINED WITH A MICRO-MANOMETER 33
13. PRESSURE VS. AXIAL DISTANCE (ENGINE IDLE CONDITION) 34
14. PRESSURE VS. AXIAL DISTANCE (ENGINE IDLE CONDITION) 35
15. PRESSURE VS. AXIAL DISTANCE (ENGINE 50% THRUST CONDITION) . 36
16. PRESSURE VS. AXIAL DISTANCE (ENGINE MID-THRUST AND 50% THRUST CONDITION) 37
17. MODIFIED ENGINE INLET 38
18. SCHEMATIC OF MODIFIED EJECTOR AND NOISE SUPPRESSOR 39
19. PHOTOGRAPH OF NOISE SUPPRESSOR 40
20. MODIFIED TEST SECTION 41
21. MODIFIED STACK TRANSLATION APPARATUS 42
22. GRATING FOR STACK FLOW RESISTANCE 43

I. INTRODUCTION

Turbojet test cells are fixed-base installations generally located at aircraft maintenance facilities for ground testing of jet engines prior to operational service. They provide an environment which closely simulates installed engine operation and allow performance monitoring and engine modifications to meet specifications. A typical test cell (Fig. 1) is usually an independently housed rectangular shaped building with an inlet stack and an exhaust stack. There are many different variations of the basic design depending on the engine to be tested and the objective of the tests.

The object of an adequate cell design is to achieve optimum operating conditions with a minimum of environmental disturbance. Pollution control is currently a major problem in the operation of test cells. A test cell must be designed to control or minimize noise and chemical pollution.

Uniform flow with low turbulence intensity is desired to facilitate accurate performance measurements. It is also desirable to have designed-in flexibility for possible future modifications which may be required for expanded testing.

As shown in Figure 1, the engine is positioned somewhere near the center of the U-shaped cell which allows the cell inlet air to develop an approximately uniform velocity profile. A portion of the cell inlet air is pulled into the engine inlet; the remainder is entrained by the engine exhaust which is directed into the augmentor tube and expelled through the stack to the atmosphere. The engine exhaust venting into the augmentor tube acts as an air ejector which pulls secondary air into the augmentor tube. The secondary air acts as a coolant as well as a diluent for the exhaust products.

The spacing between the engine tail pipe and the inlet to the augmentor tube and the augmentor design can be crucial parameters to proper engine operation since they are primary factors in determining secondary air flow. Too much secondary air flow may cause excessive pressure gradients between the engine inlet and exhaust planes leading to inaccurate performance validation. In addition, cell structural limits may be exceeded. Not enough secondary air may allow exhaust back flow to the engine inlet and hot spots in the augmentor tube and exhaust stack.

Today's stringent standards to preserve the quality of the environment are acute cell design considerations. Secondary air entrainment into the engine exhaust of a non-afterburning engine reduces the pollutant concentrations in the exhaust stack but does not appreciably change the total emittants. With afterburning operations, secondary and/or tertiary air entrainment and/or water quenching can affect the total emittants in the exhaust stack. The optimization of augmentor design and quenching methods has not been adequately determined with chemical and noise pollution minimization as a major criterion.

Many pollution abatement methods have been considered and tried (Ref. 1). They include exhaust gas scrubbing methods to remove chemical pollutants (i.e. water droplet adhesion, mechanical grid entrapment, electronic ionization and etc.) and combinations of baffles and absorbing materials for acoustic treatment.

Although most test cells are constructed similar to the one depicted in Fig. 1, "dry-house" designs are also being built and studied. Examples are the "Hush-House" such as installed at NAS Miramar, CA. (Ref. 2) for installed engine testing, and a Coanda design (Ref. 3) for noise suppression.

Current engines utilize large quantities of air and therefore require that the abatement hardware be large. Many of the current abatement methods are also complex and, therefore, expensive to both construct and operate. For these large facilities, fuel supply and cost become major considerations. Maintenance of large installations requires major considerations for scheduling, periodic replacement of damaged hardware and financial support. A major portion of support must be attributed to attracting, qualifying and maintaining a large staff of personnel.

Various analytical techniques have been employed for modeling turbojet test cells. A typical one-dimensional model has been developed by Bailey (Ref. 1). More recent analyses are two-dimensional, such as the study by Hayes and Netzer (Ref. 4). They conclude in part, "The model provides axisymmetric flow visualizations in turbojet test cells and augmentor tubes for low subsonic flow conditions. These can be used to identify regions of recirculation and to assess the amount of mixing occurring between engine exhaust gases and secondary air. Optimum locations for pollution sampling equipment can be selected by examining the numerical solutions." However, model validation is required and additional work is required for the high engine exhaust velocities which occur for military thrust and afterburning condition.

Validation of computer models requires coordinated and detailed flow field measurements under many operating conditions. These measurements are difficult to make in full scale facilities due to scheduling difficulties, operating costs, and instrumentation coordination and costs.

The above discussion indicates the need for a sub-scale test facility which can be used to perform design and operating optimization studies to both minimize emitted pollution and validate/improve models. With some

drawbacks with regard to scaling effects, the sub-scale test cell offers many advantages - low construction, maintenance and operating costs, ease of instrumentation and data acquisition, and minimum personnel.

II. METHOD OF INVESTIGATION

A one-eighth scale (1/64 scale on mass flow) NARF Alameda turbojet test cell was designed and constructed. Engine simulation was accomplished by using a variable bypass, sudden dump ramjet combustor. The ramjet was supplied with the desired amount of air and an identical amount of air was pulled into a simulated engine inlet and dumped to the atmosphere by using an ejector. The engine and test cell were instrumented for initial study of the effects of augmentor location and engine flow rate on cell augmentation ratio and flow characteristics. Initial system evaluation results were used to improve the equipment design and instrumentation for the planned test program.

III. EXPERIMENTAL APPARATUS

A. DESIGN METHODOLOGY

Construction and operation of a sub-scale turbojet test cell was found to be desirable in order to provide an inexpensive and versatile means for a) studying the effects of test cell design and engine operating conditions on cell flow characteristics and emitted pollution, and b) experimentally validating models for test cell operating characteristics. There were practicalities of construction that guided the initial design process; for example, the choice of a low cost, sub-scale air breathing engine realistic enough to obtain meaningful data. Sub-scale turbine engines were too complex and expensive and simply not available; flame tubes and torches did not simulate the airflow conditions of a jet engine. With the readily available compressed air supply from an Allis-Chalmers twelve-stage axial compressor (Fig. 2), a forced air ramjet was chosen which incorporated a variable bypass designed to simulate the exhaust of mixed-flow turbofan engines as well as turbojets. Figure 3 shows a schematic sideview (and Figures 4, 5, photographs) of the ramjet engine.

The initial investigations with the subscale turbojet test cell are being directed at augmentor design effects and analytical model validation. To this end it was only necessary to simulate the engine exhaust jet through the nozzle total temperature and pressure ratio. For these limited characteristics, a sudden-dump ramjet burner can with by-pass air provides an adequate simulation of the jet exhaust for operations from idle through military with afterburner. To properly simulate the combustion process within current turbojet and turbofan combustors requires pressures between eight and twenty atmospheres. Using the higher pressures is especially important if the subscale model is to be used to study the effects of engine operation

and test cell design on the quantity and composition of emitted pollutants. Current efforts include construction and testing of a high pressure burner in which mixture ratio and fuel distribution can be readily varied.

It was decided to simulate TF-41 test cell conditions with a one-eighth scale model. The scale was selected on the basis of practicality of construction, economy of operation, the available air supply, and the desire to maintain velocities and similar Reynolds numbers to the full-scale test cell. The engine was scaled in diameter by one-eighth, resulting in the mass flow rate being scaled by 1/64. This was done to maintain flow velocities the same as in the full-scale test cell.

The overall TF-41 test cell length was reduced from 125 feet to 15.6 feet, cell height and width from 18 feet to 2.25 feet and engine diameter from 31 inches to 3.88 inches (Figs. 6, 7, 8). Engine air flow rates for the model were taken as 1/64 of those of a TF-41 engine; namely $\dot{m}_{idle} = 1.56$ lbm/sec and $\dot{m}_{military} = 4.11$ lbm/sec.

Once the dimensions of the engine and cell were determined, the associated piping and hardware were sized to supply the system with the required air and fuel flow rates.

The one-eighth scale model, while exhibiting air flow velocities of the full scale versions, reduced Reynolds numbers by a factor of one-eighth. Therefore, results obtained from extensive sub-scale testing should be validated with selected full scale tests.

B. DESCRIPTION OF APPARATUS

1. Ramjet Engine and Piping

The ramjet (Fig. 3) consisted of an inlet, combustor, nozzle, and bypass air ducting. The combined airflow through the combustor and bypass duct were matched to the suction airflow through the engine intake. The original

intake consisted of a four-inch diameter steel pipe fitted with a bell mouth. Two three-inch pipes were attached between the intake pipe and the six-inch suction line which lead to the air ejector. The suction airflow rate was measured with a standard ASME-type orifice installed in the six-inch line.

Two three-inch pipes with accompanying orifices were used to supply combustor (primary) and bypass (secondary) air flow to the aft section of the ramjet. Fuel was injected into the primary air supply through fifty 0.010-inch diameter holes in a ring manifold approximately 18 inches upstream of the combustor. The combustor was of sudden expansion (or dump) configuration and was designed to hold a flame in the recirculation zone in the combustor can immediately downstream of the step. Dump burners operated at low pressures, exhibit very narrow flammability limits (Ref. 5). Combustion of the JP-4 fuel was sustained over wide mixture ratio limits by the continuous operation of a methane-oxygen torch placed in the combustor wall 1 3/4 inches downstream of the step (Fig. 3). The combustor can was a thin-walled inconel tube. By-pass air was used to cool the inconel tube as well as to lower exhaust temperatures in order to further simulate mixed-flow turbofan operation. Primary and secondary air-flow rates were controlled by hand-valves installed downstream of the flow orifices.

The fuel supply system consisted of a nitrogen pressurized tank of JP-4 jet fuel. The pressurized fuel was filtered prior to passing through a solenoid valve and into the ring manifold. Metering of the fuel was accomplished by installing a cavitating venturi in the fuel line prior to the manifold. The function of the venturi was to permit the adjustment of fuel flow as a function only of upstream pressure. The fuel flow rates vs. upstream pressures for the two cavitating venturis employed are presented in Fig. 9.

2. Test Cell and Exhaust Stack

The cell test section and exhaust stack were separately bolted to twin I-beam rails. These sections were essentially independent of the fixed plumbing and ramjet engine for comparative ease of longitudinal realignment. The test section was constructed of reinforced 3/4-inch plywood with an inlet flow straightening section consisting initially of 1 1/2-inch thick aluminum honeycombing (1/4-inch mesh) and two layers of window screening. The installation permitted selective addition or removal of flow straighteners in a slide-in-frame arrangement. In addition, the inlet included a square sheet-aluminum bell-mouth. Since the model test cell was mounted above ground level on rails, the complexity of a vertical intake was avoided. The cell also included removable plexiglass sides for engine access, visual observation, and engine exhaust opacity measurements.

A plate-steel exhaust stack, separate from the test section, allowed augmentor tube interchangeability and, if desired, the introduction of ambient tertiary air. The stack was fitted with an asbestos insulated 45-degree deflection plate.

3. Augmentor Tube

One of the basic studies to be conducted was the effect of the augmentor tube position and design on flow conditions and augmentation ratio. It was therefore necessary to plan for augmentor tube interchangeability and adequate instrumentation. The initial installation consisted of an eight-inch diameter stainless steel pipe mounted horizontally along the ramjet engine centerline, with a 2.25-inch space between the engine exhaust nozzle and the mouth of the augmentor tube. The walls of the 4.44 feet long tube were fitted with twelve evenly spaced static pressure ports.

4. Instrumentation

The sub-scale test cell was fully instrumented for the calculation of air flow rates, cell temperatures and pressures, and velocity profile measurements at the cell entrance, engine inlet, augmentor tube exit and stack exhaust (Fig. 10).

A 24 port, automatic-stepping Scanivalve was utilized to measure the upstream and downstream static pressures across each of the three airflow measuring orifices (Figs. 6 and 10); the static pressures at the cell inlet, engine inlet, engine exhaust, and exhaust stack and the twelve augmentor tube static pressures.

A Flow Corporation Model MM-2 Micromanometer was used with a traversing pitot tube mounted horizontally twelve inches behind the flow straightener section (Fig. 7). They were used in the initial investigation to measure the inlet flow velocity profile. The velocity profiles provided indications of flow distortion and allowed cell augmentation ratio to be calculated.

5. Data Acquisition

The automatic data acquisition system consisted of a fully programmable Hewlett-Packard 9830 A desk top Calculator with a HP-9867 B Mass Memory Storage unit, and a B. and F. Model SY133 data logger coupled to a paper punch tape printer (Figs. 11). The system provided automatic scanning of 24 channels of individual pressure readings and temperature measuring thermocouples. The raw data were punched on paper tape during each run and then entered via a digital tape reader into the HP-9830 A Calculator for processing and storage in the form of both raw and reduced data.

IV. INITIAL SYSTEM EVALUATION

The matching of flow rates between the engine intake and the summation of the combustor and bypass air supplies was effected with comparative ease for nominal test conditions. When very accurate flow rate matching was desired, the manual valve adjustment process became somewhat time consuming. The control of the flapper valve on the six-inch suction line to the air ejector was found to be extremely sensitive. A very low gear ratio controller would be required for remote control of that particular valve. The overall "cross-talk" sensitivity among the competing air supply lines was found to be negligible.

The engine component testing required several attempts and modifications to achieve ignition and stable flame holding without blow-off. A Champion VR-1 spark plug (Fig. 4) was initially employed for ignition but was found to be inadequate. It was replaced by a methane-oxygen torch (Fig. 3). The methane-oxygen torch performed adequately except for combustor can air flow rates above approximately 0.8 lbm/sec. At the high flow rates torch blow-off would occur. Locating the torch further upstream in the recirculation region should eliminate this problem.

The augmentor tube pressure profiles showed a considerably lower than atmospheric maximum pressure until the exhaust stack exit area was restricted with its own dust cover plate. In addition, the augmentor pressure profiles also indicated the possibility of leakage around the seal between the augmentor and exhaust stack.

Air ejector noise proved to be a community annoyance, partially due to the position of the laboratory facilities at NPS relative to the surrounding hills.

The installation of the plexiglass viewing ports (Fig. 8) proved beneficial in determining engine light off and witnessing normal engine operation. Further modifications to make the plexiglass a permanent part of the cell structure were required with definite attention paid to engine bay access as well as maintaining air tight integrity.

The automatic data acquisition system performed adequately and was considered to be a major attribute of the facility.

The micromanometer and traversing pitot tube were used to acquire velocity data at the cell inlet. It was found that this apparatus lacked sufficient response time for obtaining reliable data without excessive testing durations.

The velocity profiles indicated that aerodynamic acceleration occurred around the inlet ramps (Fig. 12). It will be necessary to move the pitot probe further aft from the inlet if flat velocity profiles are to be used for ease of determining cell augmentation ratio.

Pressure profiles were obtained for several flow conditions and two separate augmentor-to-engine spacings; flush and two inches separation (Figs. 13, 14, 15 and 16). Both cold and reacting engine flow were employed. The profiles showed that there was essentially no change in pressure within the exhaust stack except at the very high flow rates, due to the fact that the stack resistance was too low. This resulted in erratic pressure profiles near the augmentor exit. The pressure profiles showed the expected sharp decrease in pressure at the entrance section of the augmentor tube. Larger augmentor diameters can be expected to exhibit less rapid pressure variations. Since the first pressure tap was located four inches downstream of the tube entrance, it was not possible to determine the exact location of minimum

pressure. Additional static pressure ports in the first four inches of augmentor tube are desirable to establish a refined pressure profile. The initial results obtained in this investigation are compared to the computer predictions of the Hayes/Netzer study (Ref. 4) in Table 1.

TABLE I

COMPARISONS OF EXPERIMENTAL DATA TO ANALYTICAL MODEL

Item	Full Scale Analytical Model	Sub-scale Experimental Results	
Engine Dia.	25"	3.5"	3.5"
Augmentor Dia.	6'	8"	8"
D_{aug}/D_{eng}	2.88	2.29	2.29
Aug. Ratio (A.R.)	0.5 (specified)	0.72	0.61
Eng. Operating Condition (Simulated)	IDLE	IDLE	IDLE
Aug.-Eng. Spacing	.25 D_{aug}	.25 D_{aug}	0
Min. Pressure Point in Aug.	.4 D_{aug}	0-.5 D_{aug}	0-.5D_{aug}
Max. Pressure Point in Aug.	3.2 D_{aug}	4 D_{aug}	4.5 D_{aug}
Min. to Max Pressure Differential	.36 psi	.14 psi	.15 psi

In the computer simulation the augmentation ratio must be specified and was therefore not identical to that obtained experimentally. These initial comparisons show good agreement except for the minimum to maximum pressure differential. However, as indicated above, additional pressure taps are required in the augmentor tube to locate and measure the minimum pressure. The computer predictions also indicated negligible effect of engine-augmentor spacing on augmentor pressure rise for the low thrust conditions with low augmentor-engine diameter ratios. The initial data appear to agree with this result.

V. SYSTEM MODIFICATIONS

A summary of the system deficiencies which were identified in the initial checkout tests are listed in Table II. Also indicated are the solutions currently being implemented.

TABLE II

SYSTEM DEFICIENCIES AND IMPLEMENTED MODIFICATIONS

DEFICIENCY	IMPLEMENTED MODIFICATION
Intake suction resistance too high	Change from 4" to 5" inlet with one exit pipe
Stack resistance too low and not adjustable	Add grating to exhaust stack
Stack-Augmentor Seal	Use welded joint
Stack axial motion difficult	Put stack on rollers and rail
Plexiglass sides difficult to remove	Use hinged sides
Ejector exhaust noise excessive	Change ejector design and add noise suppressor
Inadequate details of augmentor flow field	Additional pressure and temperature measurements, pitot rake
Test cell velocity profile measurement	Use hot-wire probe for faster response time

The 4" engine intake together with the 3" connecting lines (Figs. 3-5) produced high flow resistance in the suction system. This resulted in the ejector apparatus requiring high flow rates and producing excessive noise levels. In addition, the required high flow rates reduced the available air required in the burner and bypass system. To help eliminate these problems the intake of the suction system was replaced with a single 5" system as shown in Fig. 17. In addition, the ejector air supply was provided directly from the air reservoir (Fig. 18) and a large noise suppressor was added to the ejector (Figs. 18, 19).

To improve the ease of internal test cell modifications and augmentor tube movement the plexiglass side walls were hinge mounted (Fig. 20) and the exhaust stack was placed on a roller-rail apparatus (Fig. 21).

In order to better simulate the flow resistance in full scale test cell exhaust stacks an interchangeable grating was placed within the upper portion of the stack (Fig. 22). The initial design incorporated a 50% blockage.

To obtain better flow field details for model validation the quantity of instrumentation was significantly increased. The number of pressure taps was increased to 27 for the eight inch augmentor tube. They begin at the augmentor inlet and are closely spaced near the entrance and exit section. The additional pressure measurements required the use of a 48 channel Scanivalve. In addition, thermocouples were added to the augmentor tube and a pitot probe rake was inserted into the augmentor tube from the exhaust stack. The rake can be translated from the augmentor exhaust to the engine exhaust.

To improve flow visualization, several vertical rods with tufts were positioned within the test cell. A hot wire probe will be used in place of the pitot tube and micromanometer to obtain cell velocity profiles. This results in more rapid data acquisition and less error.

VI. SUMMARY OF CURRENT INVESTIGATION

The improved test cell apparatus and instrumentation are currently being utilized in three related investigations; 1) augmentor tube optimization, 2) analytical model validation, and 3) effect of cell design and operation on particulate emission levels.

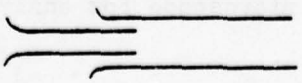
A. AUGMENTOR TUBE OPTIMIZATION

The optimization of augmentor tube design is proceeding along two directions. A dry-house used for installed engine testing should incorporate an "optimum" augmentor design which can pump the minimum secondary air while

maintaining the structural integrity of the augmentor tube (including any acoustic linings). Various film cooling methods are being tested. For conventional test cells an "optimum" augmentor many times is one that can pump the maximum secondary air without excessive pressure drop across the engine. This is done to reduce the visible exhaust to below a Ringleman number of one. Tertiary air designs are being studied for this purpose. These devices attempt to use the augmentor to also pump air from outside the cell into the exhaust stack.

Both "optimum" designs depend upon the engine operating characteristics as well as the augmentor design. Augmentor design variables include (a) engine-augmentor spacing, (b) diameter and length, (c) inlet configuration, and (d) any secondary gaseous or liquid injection. Augmentor length is not a critical design variable providing that it is between 6 and 9 diameters (Ref. 2). A summary of the augmentor optimization study is presented in Table III.

TABLE III. AUGMENTOR DESIGN STUDY

Parameter	Variables Considered
Augmentor Diameter	D = 8, 10, 12 in.
Inlet Design	Flow Inlets: 
Engine Operating Conditions	Nozzle Total Pressure (atm): 1.5, 2.0, 2.5
	Nozzle Total Temperature (°R) 520, 1000, 2500
	Nozzle Exit Mach No.: < 1 to > 1
	Nozzle Flow Rate: Idle to Military
Engine-Augmentor Spacing	0.25 D overlap to 0.5 D gap
Film Cooling and Tertiary Air	

B. ANALYTICAL MODEL VALIDATION

Detailed measurements will be made of the flow field within the test cell in order to validate analytical models. The data will be compared with typical one-dimensional (Refs. 1) and two-dimensional (Refs. 4, 6) model predictions. Measurements which will be made for this study (as well as for augmentor optimization) are presented in Table IV.

Table IV SUMMARY OF MEASURED PARAMETERS FOR MODEL VALIDATION

Engine:	Flow Rate, Total Temperature, Total Pressure, Turbulence Intensity of Exhaust Jet
Test Cell:	Velocity, Temperature, and Pressure Distributions, Flow visualization with tufts
Augmentor Tube:	Axial and Radial Variations in Pressure, Velocity, Temperature, Turbulence Intensity
Stack:	Pressure, Temperature

C. PARTICULATE EMISSION LEVELS

A small dump burner will be employed to generate varying amounts of particulates. The water-cooled burner will operate at 10 atm and will use two sonic nozzles to reduce the pressure to tailpipe pressure. The exhaust from the burner will be fed into the existing low pressure tailpipe/afterburner apparatus. Initial measurements will be made for the effects of engine operating characteristics and cell design on particulate concentrations. In particular, transmissometers will be used to measure the variation in opacity between the jet and stack exhausts. Later studies will be concerned with the effects of fuel additives on the amount and composition of particulates. The latter studies will utilize sampling probes and a scanning electron microscope for analysis of the particulates.

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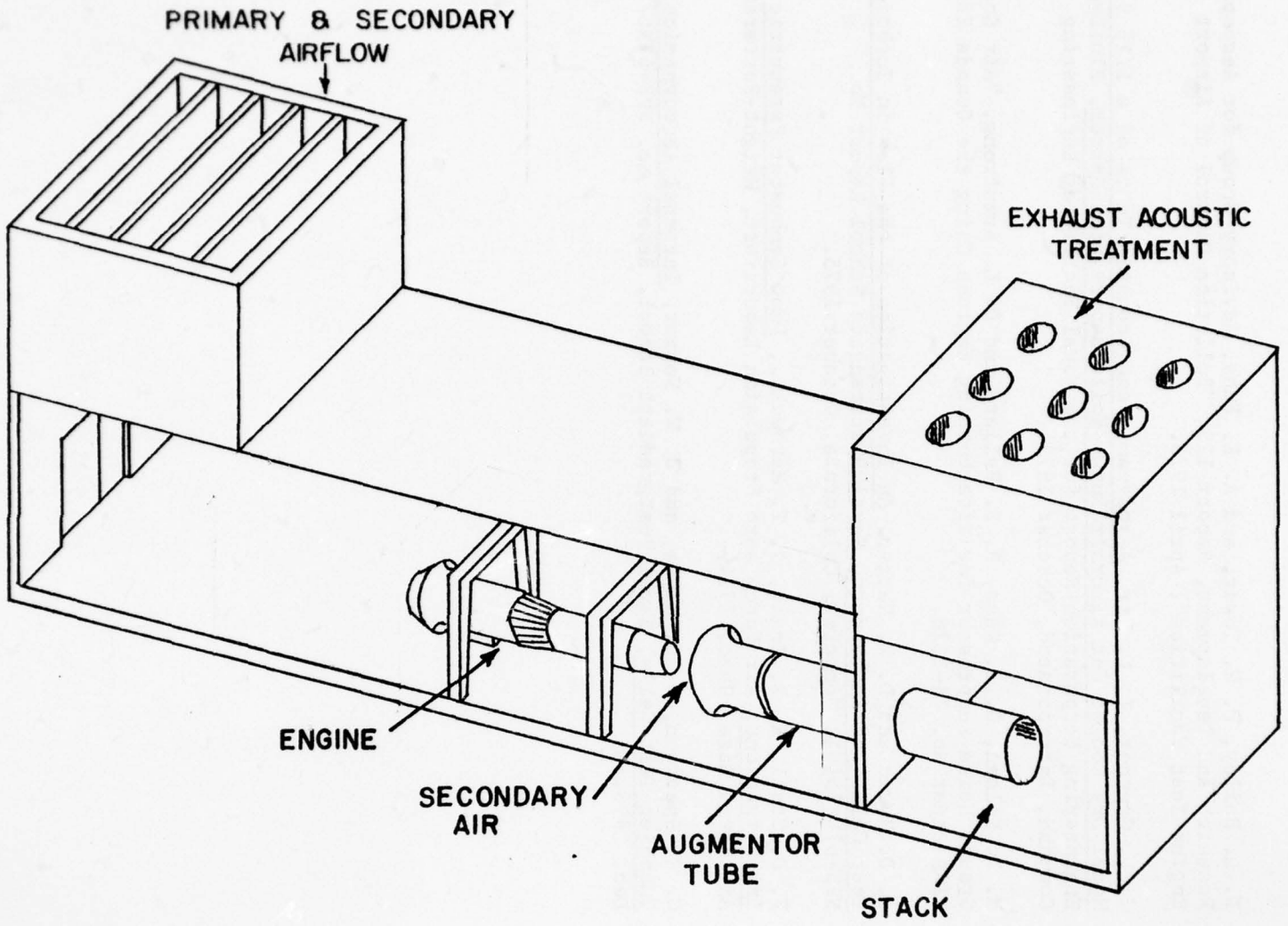


Fig. 1. Schematic of Typical Turbojet Test Cell

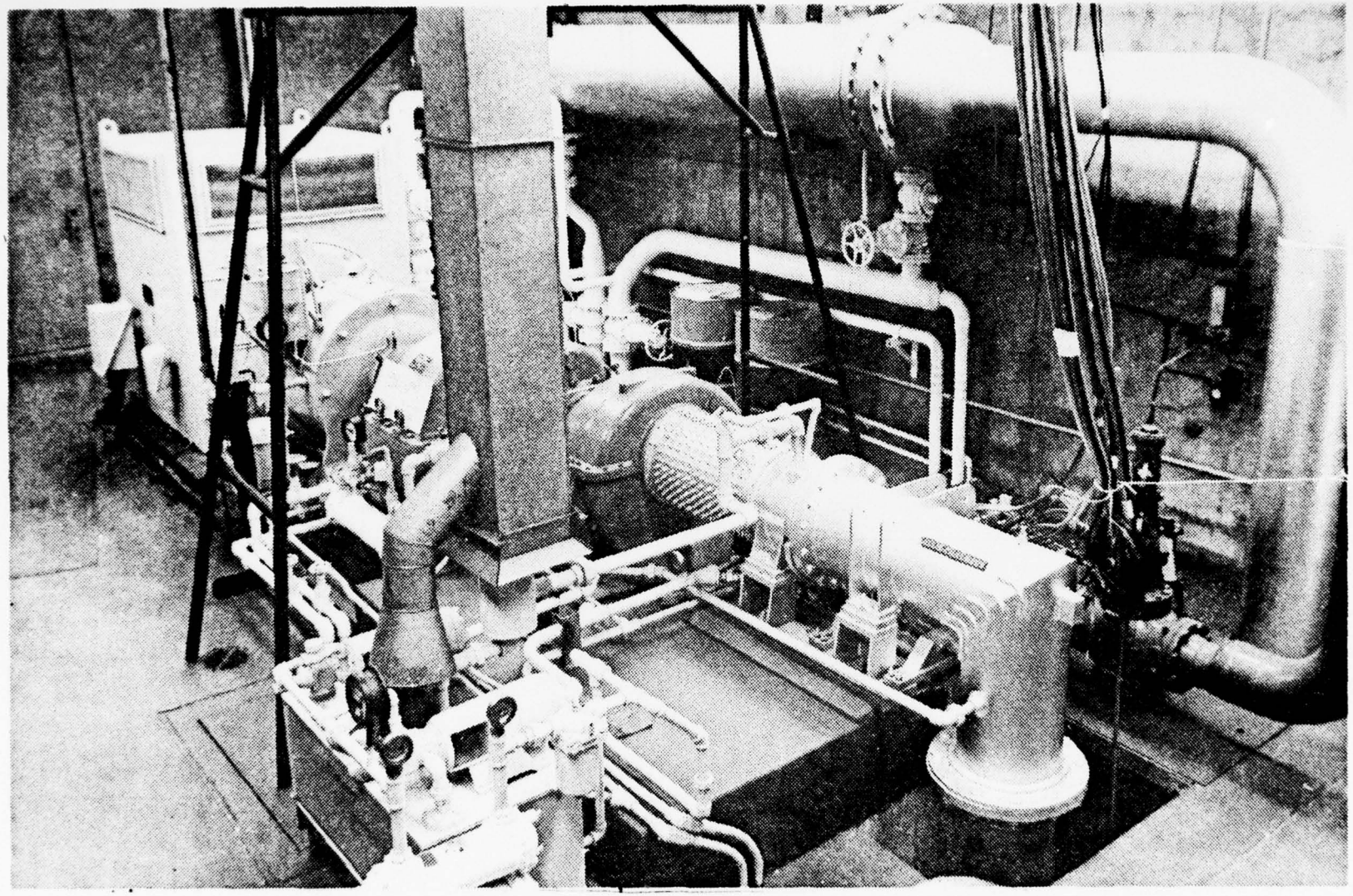


Fig. 2. Photograph of 12-Stage Allis Chalmers Axial Compressor

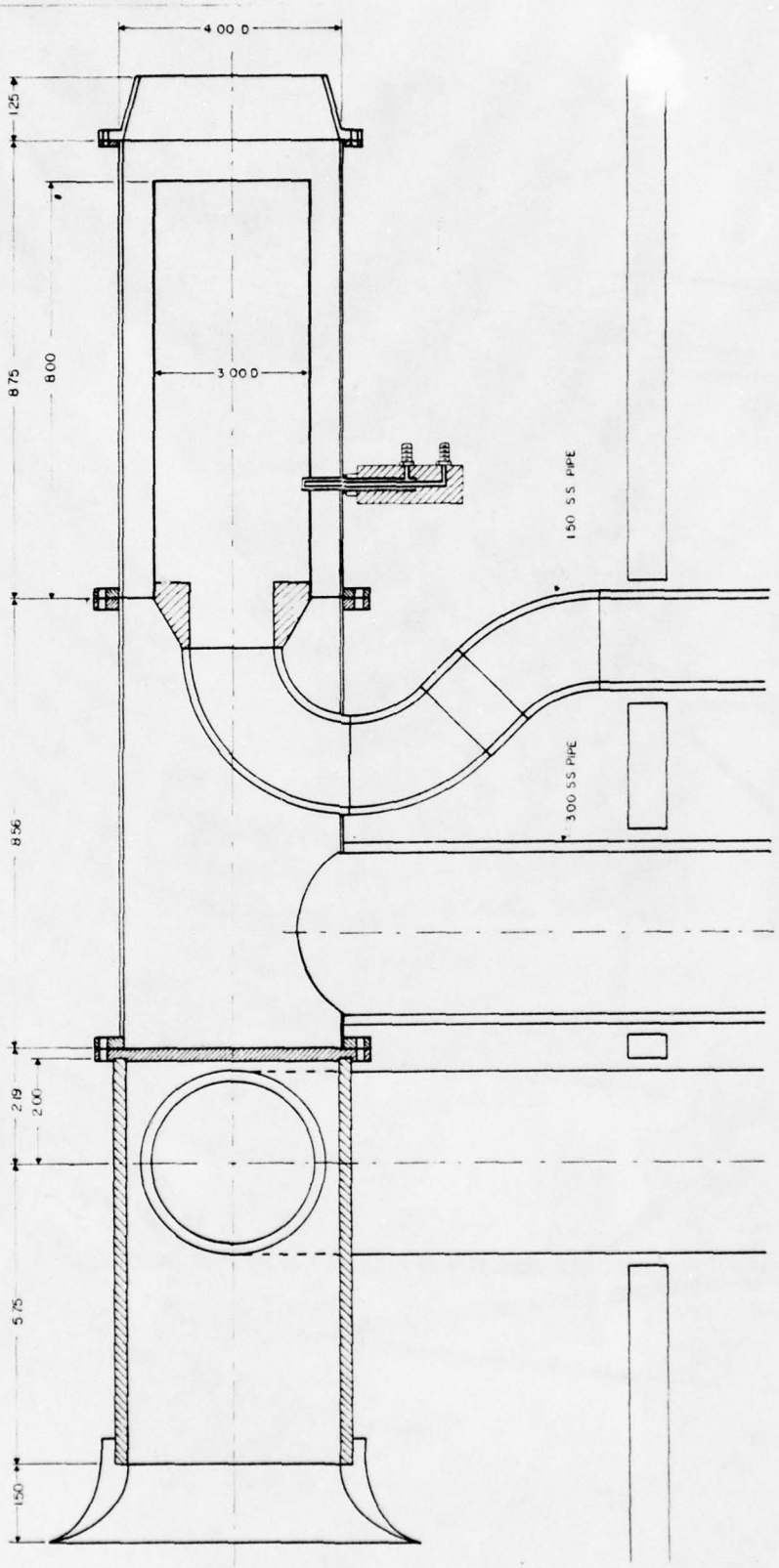


Fig. 3. Schematic of Ramjet Engine

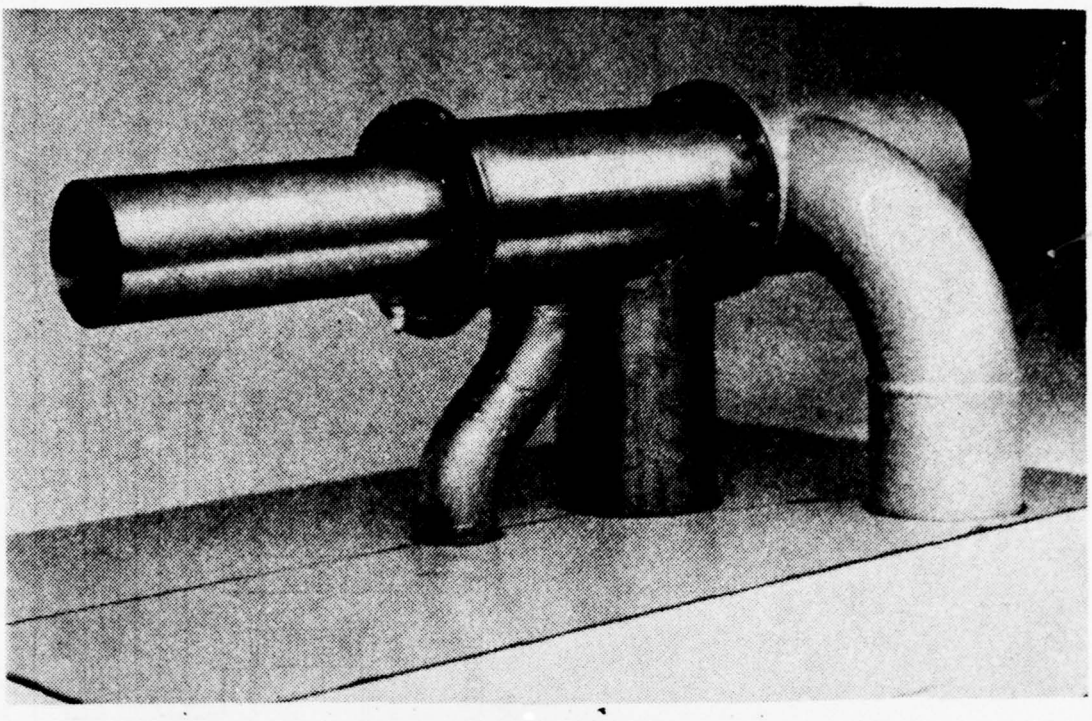


Fig. 4. Photo of Ramjet Without Bypass Air Shroud

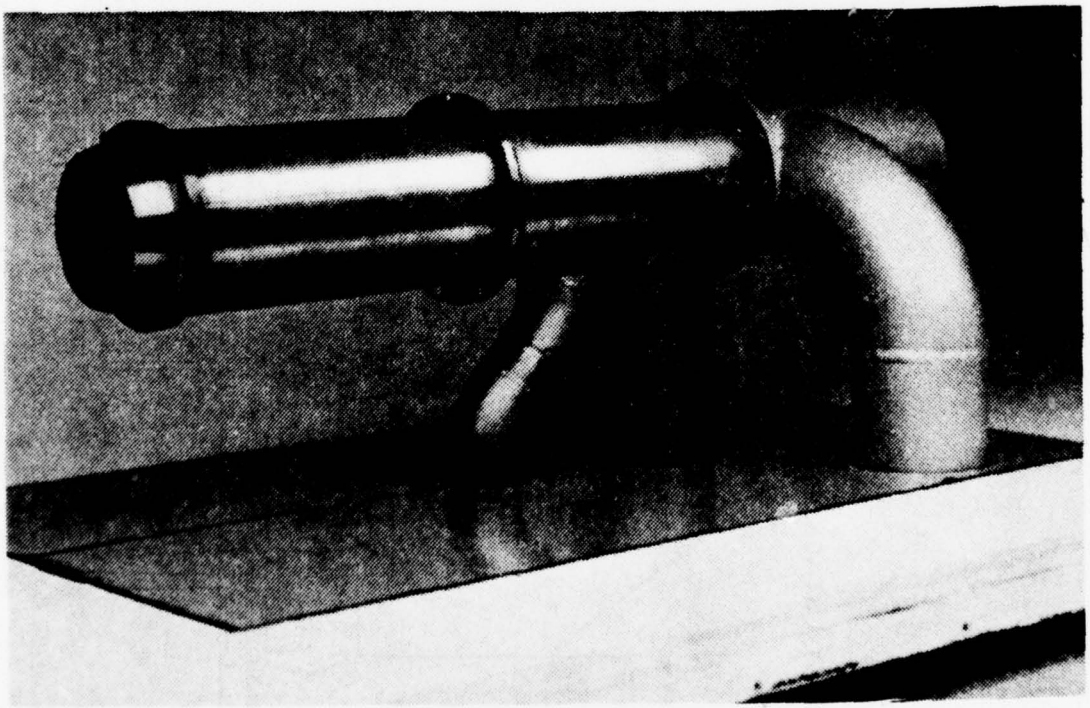


Fig. 5. Photo of Ramjet Assembly

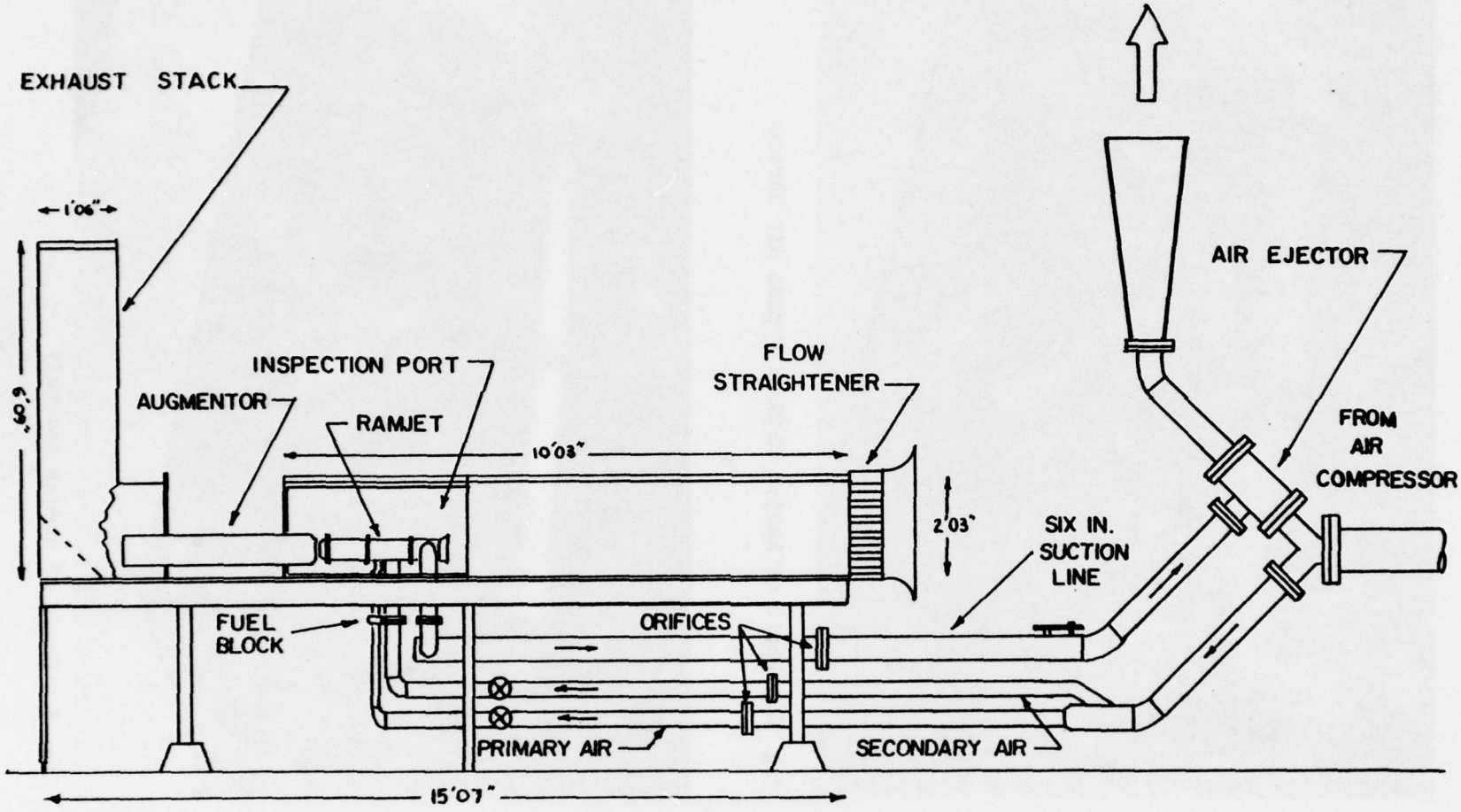


Fig. 6. Schematic of Initial 1/8 Scale Turbojet Test Cell

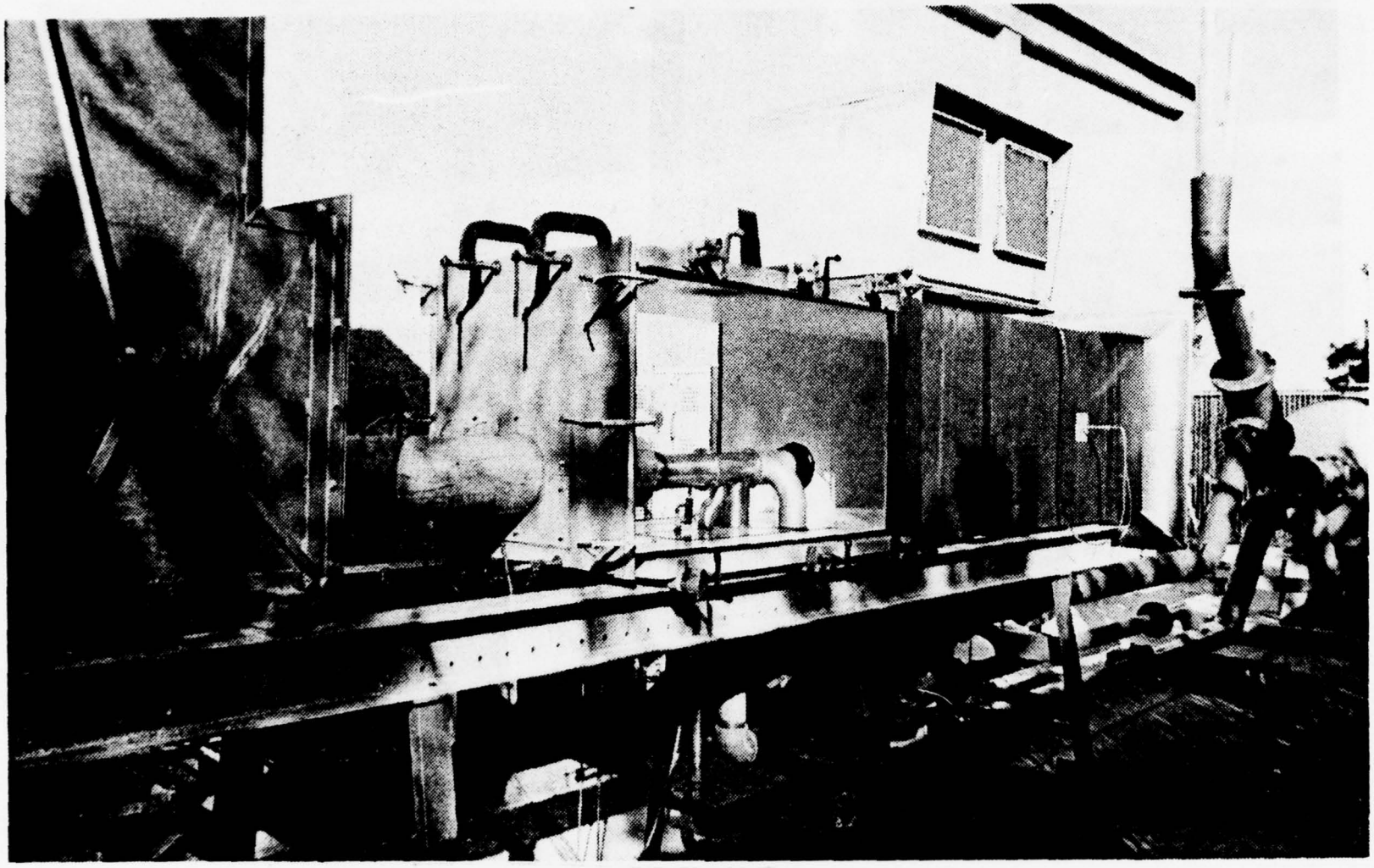


Fig. 7. Photograph of Initial 1/8 Scale Turbojet Test Cell

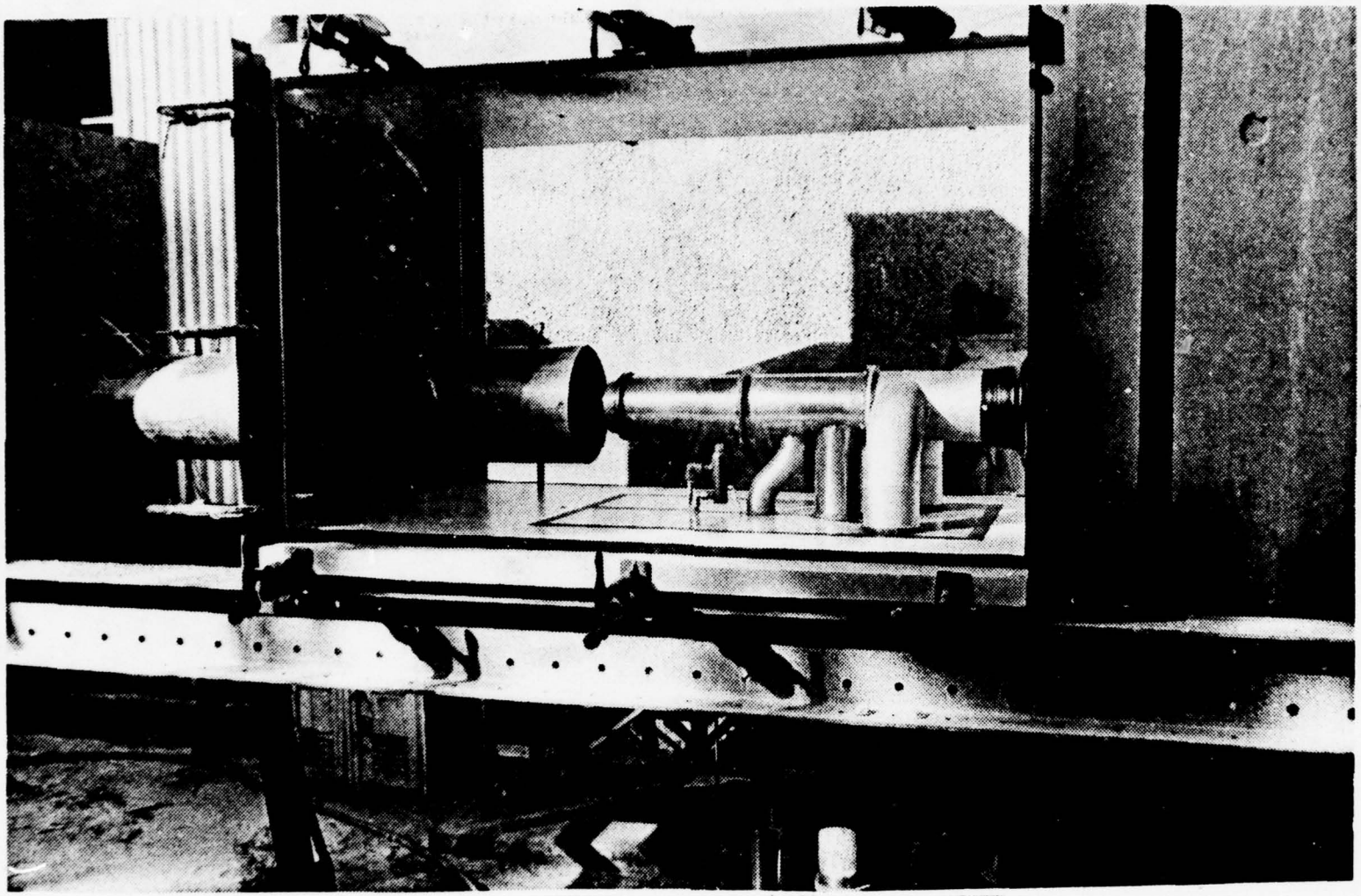


Fig. 8 Photograph of Initial 1/8 Scale Turbojet Test Cell - Test Section

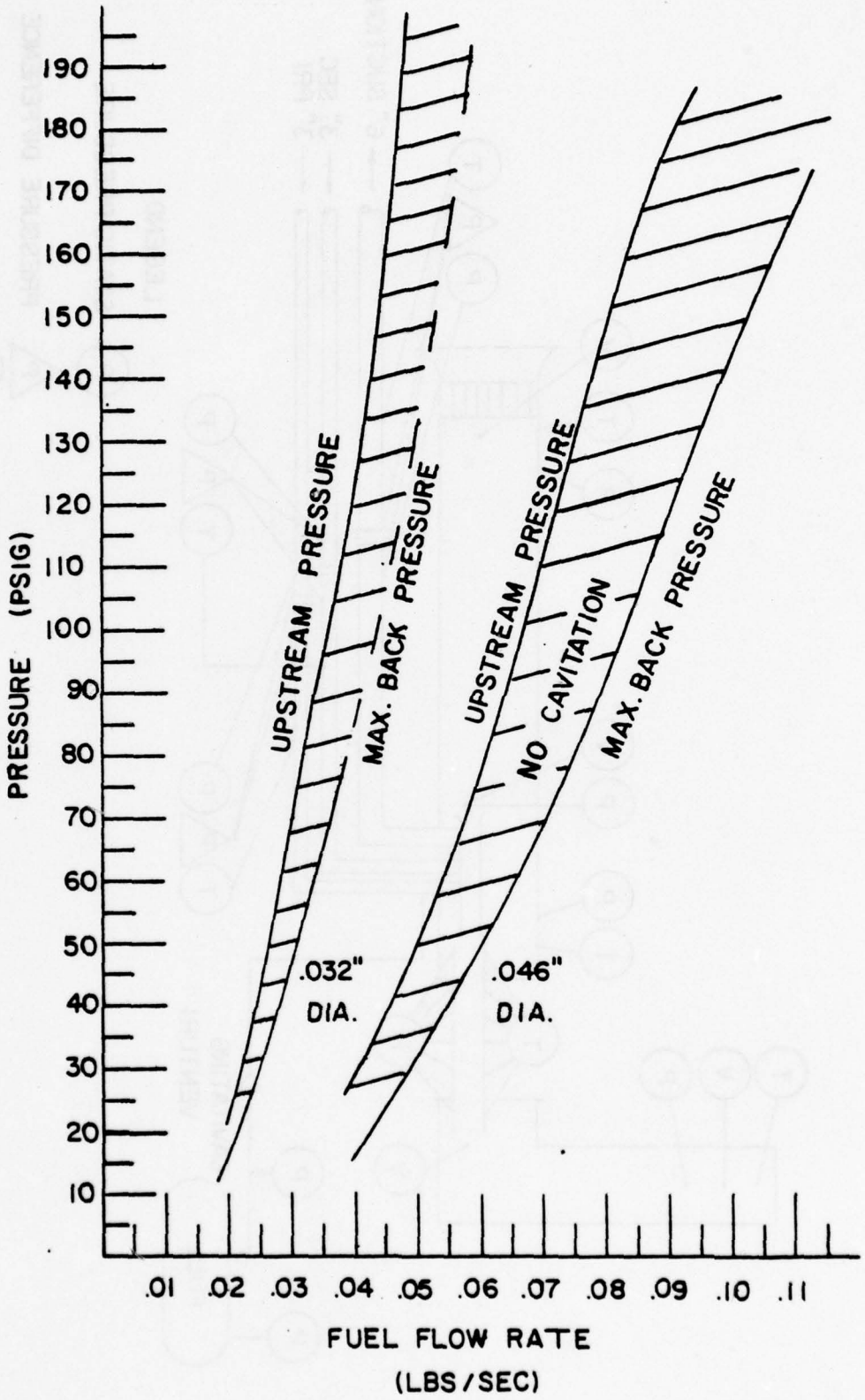


Fig. 9. Cavitating Venturi Pressure vs. Flow Rate

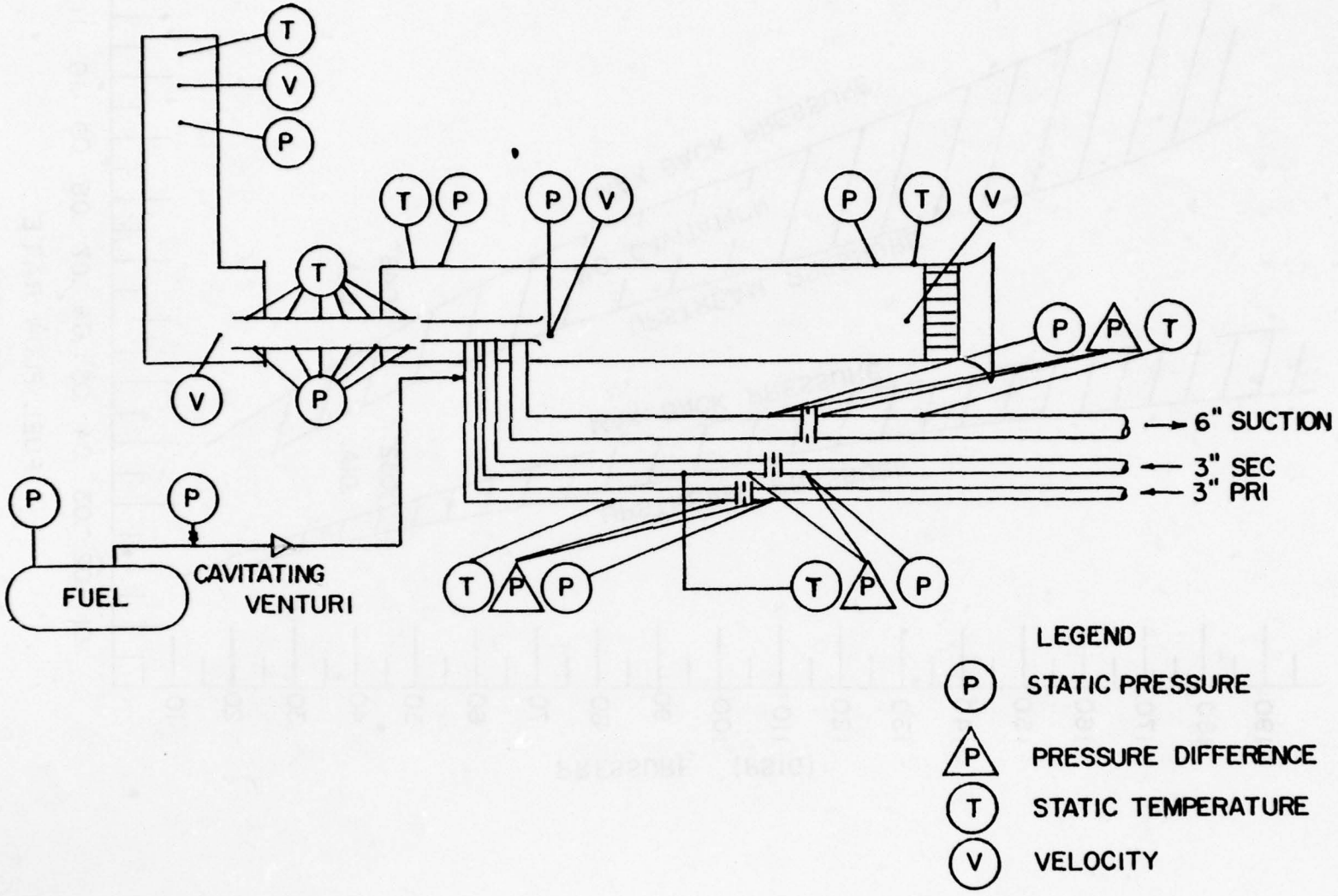


Fig. 10. Data Sensor Locations on the 1/8 Scale Facility

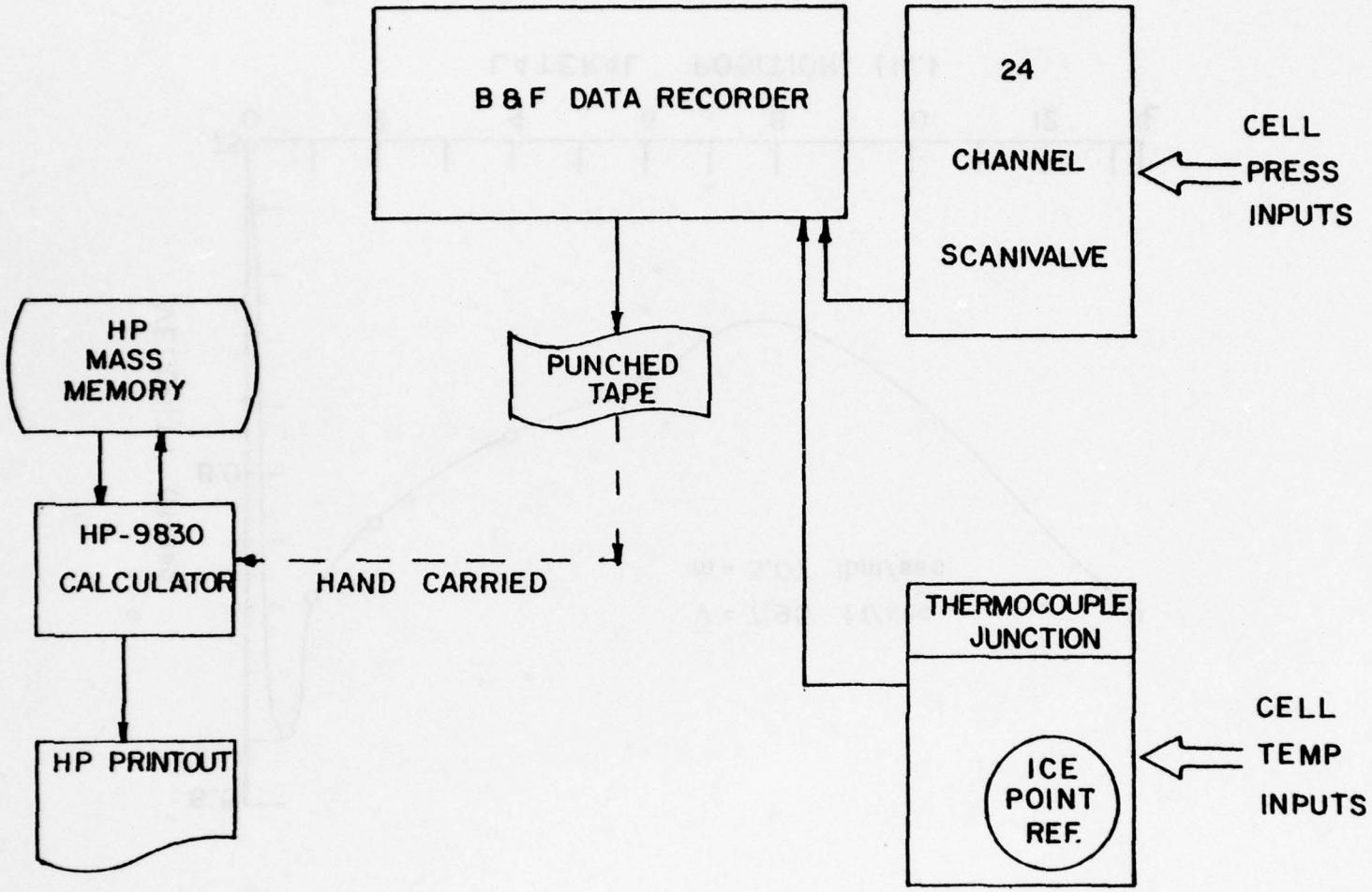


Fig. 11. Schematic Diagram of Data Reduction System Utilizing the Hewlett-Packard 9830A Calculator

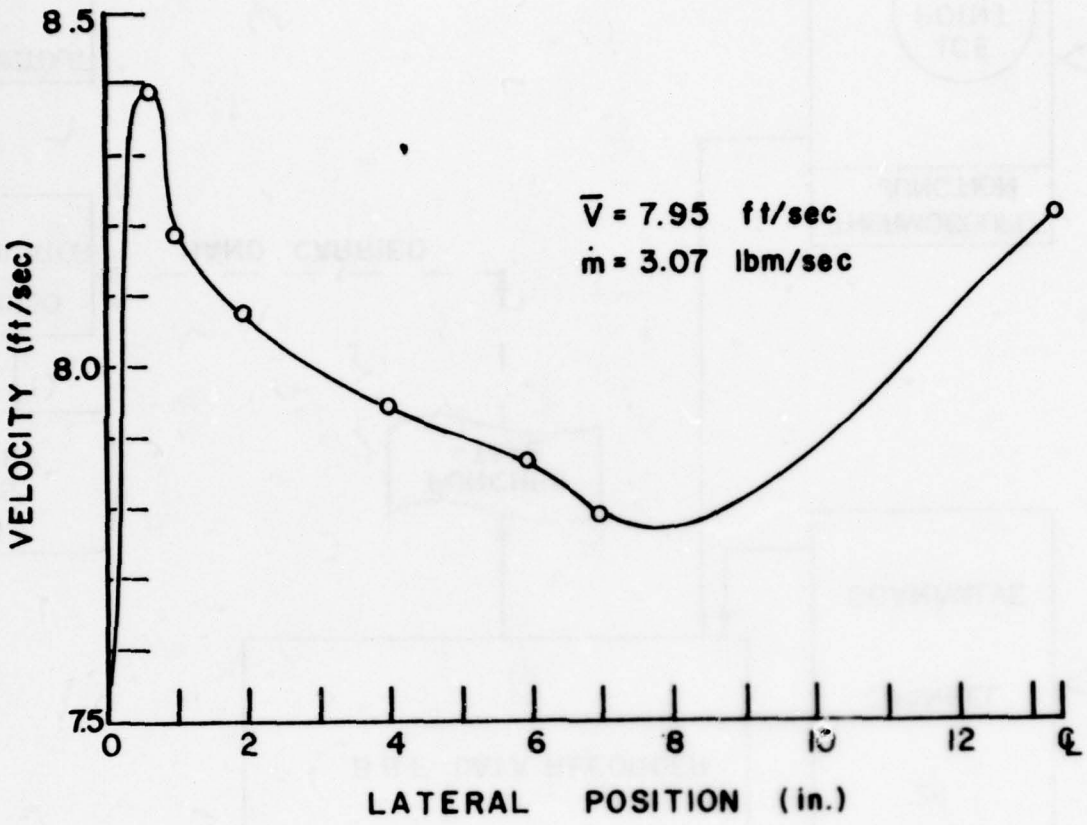


Fig. 12. Typical Inlet Velocity Profile Obtained with a Micromanometer

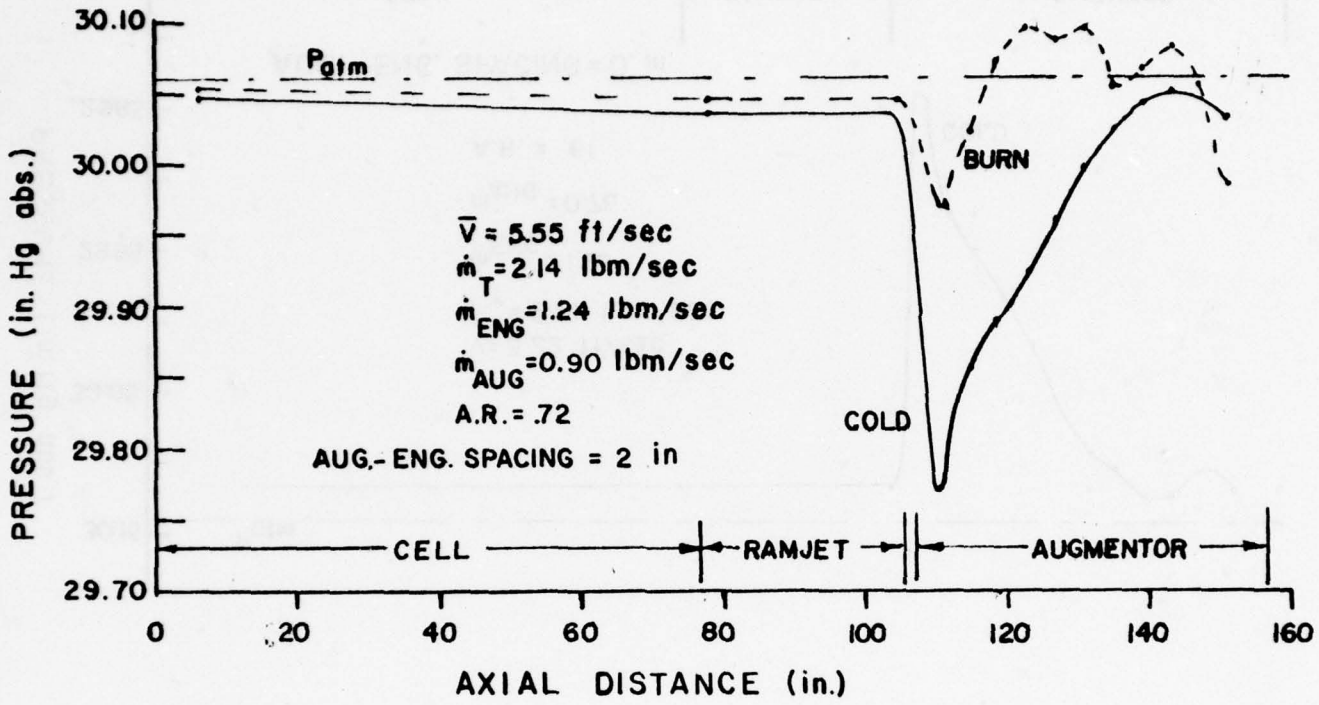


Fig. 13 Pressure vs. Axial Distance (Engine Idle Condition)

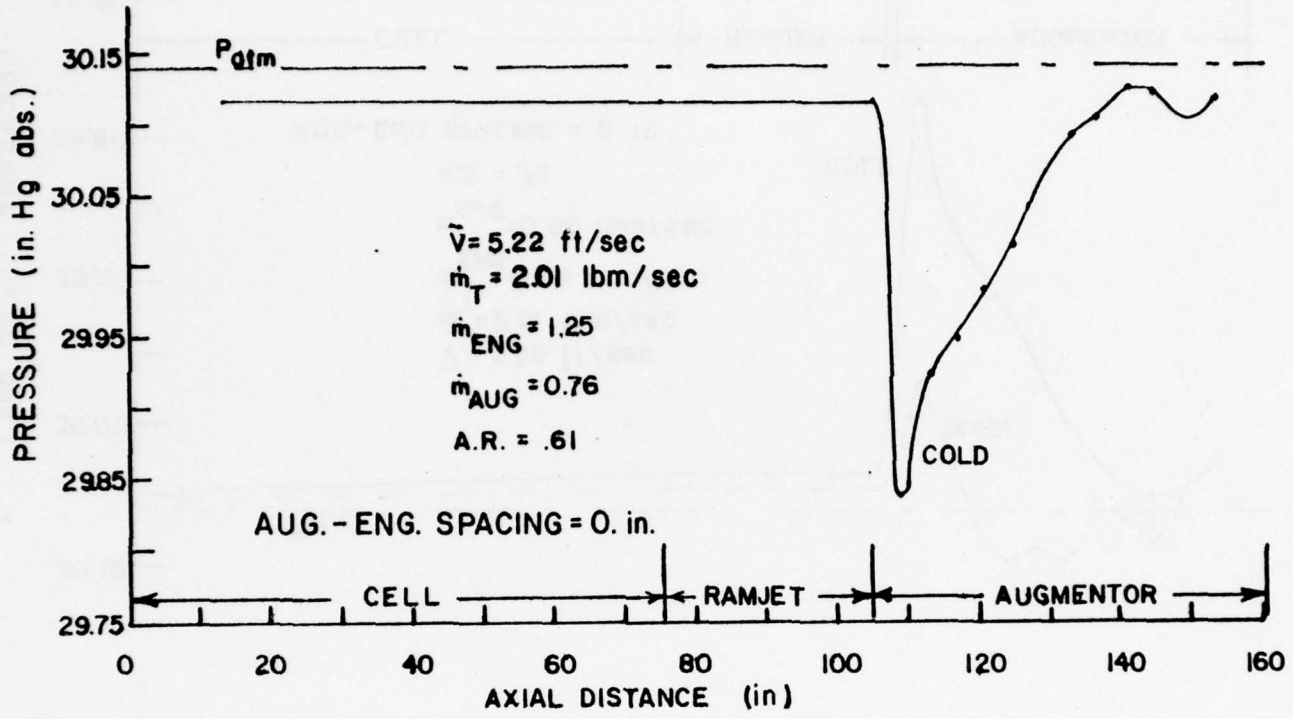


Fig. 14. Pressure vs. Axial Distance (Engine Idle Condition)

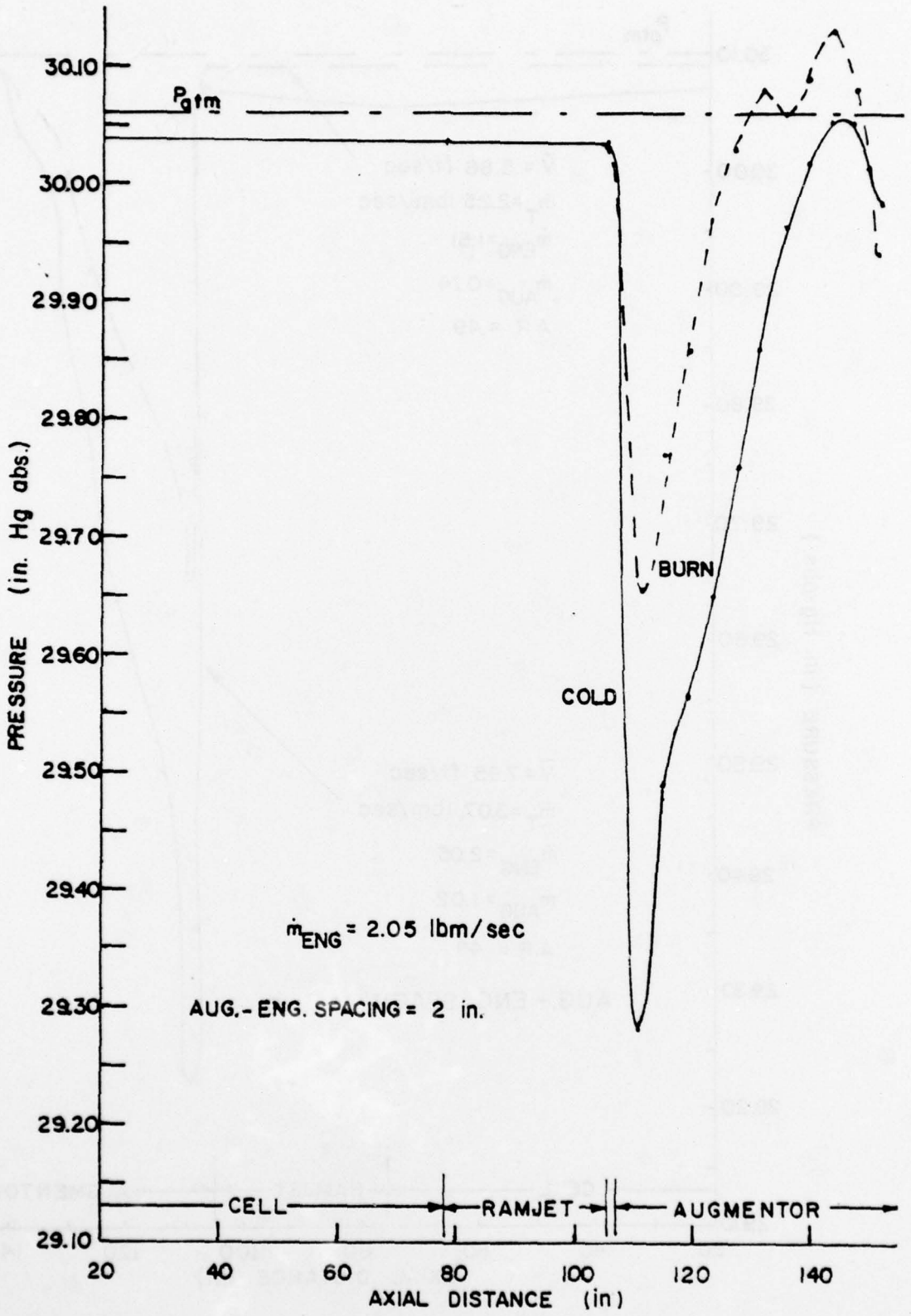


Fig. 15. Pressure vs. Axial Distance (Engine 50% Thrust Condition)

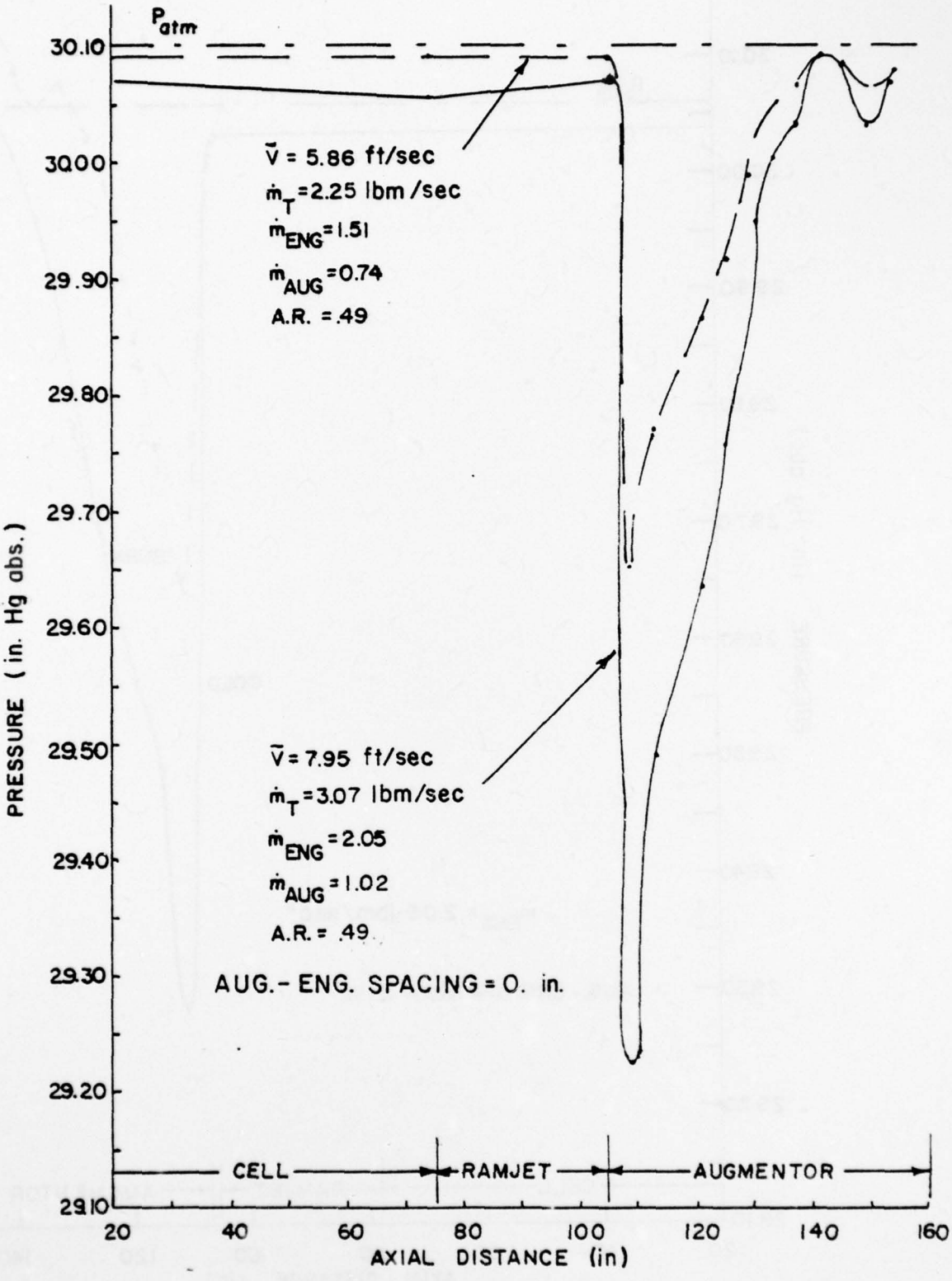


Fig. 16. Pressure vs. Axial Distance (Engine Mid-Thrust and 50% Thrust Condition

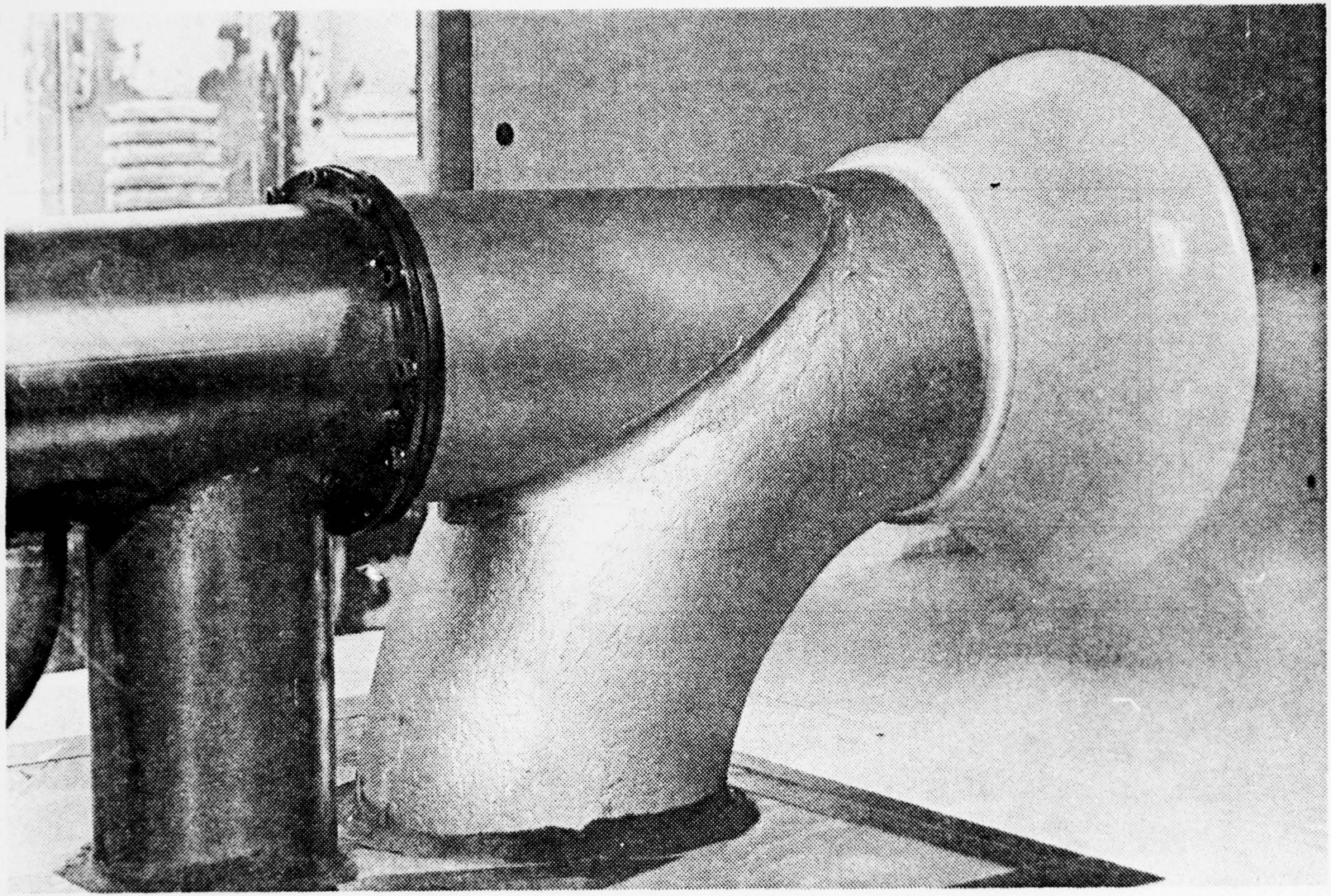


Fig. 17. Modified Engine Inlet

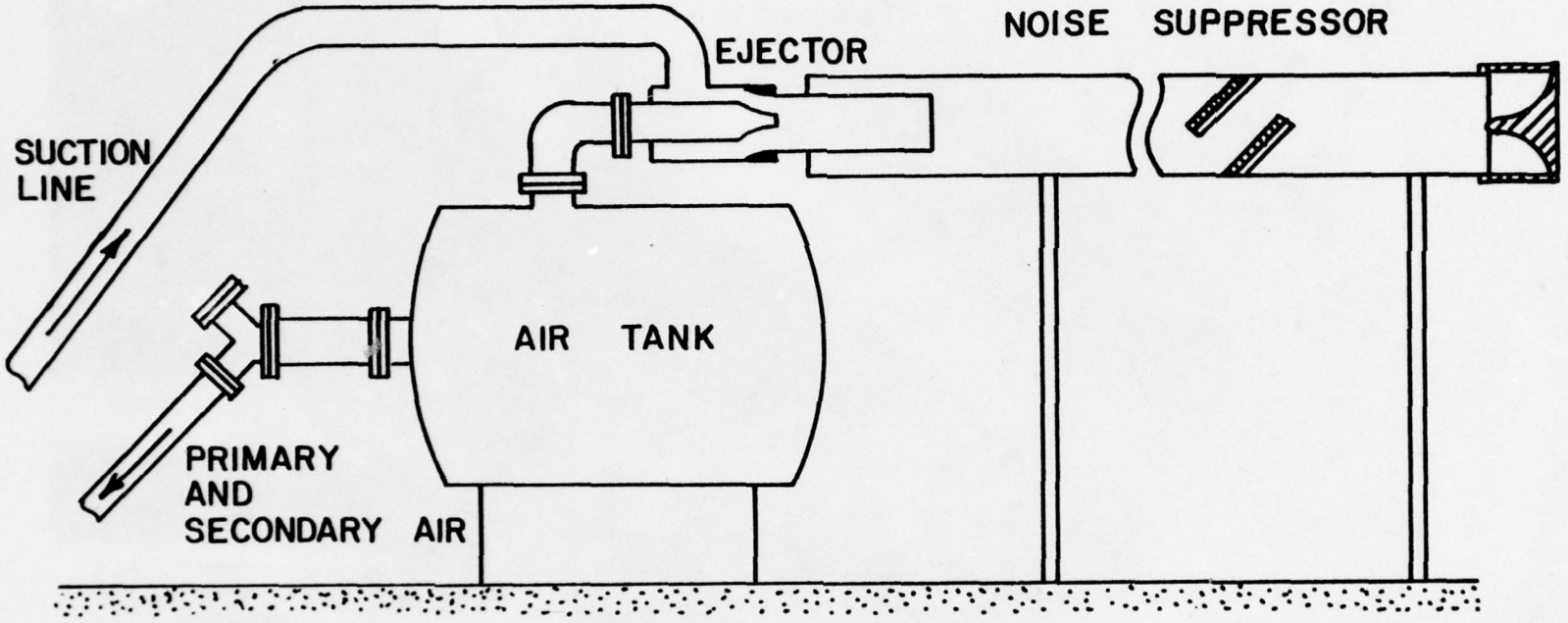


Fig. 18. Schematic of Modified Ejector and Noise Suppressor

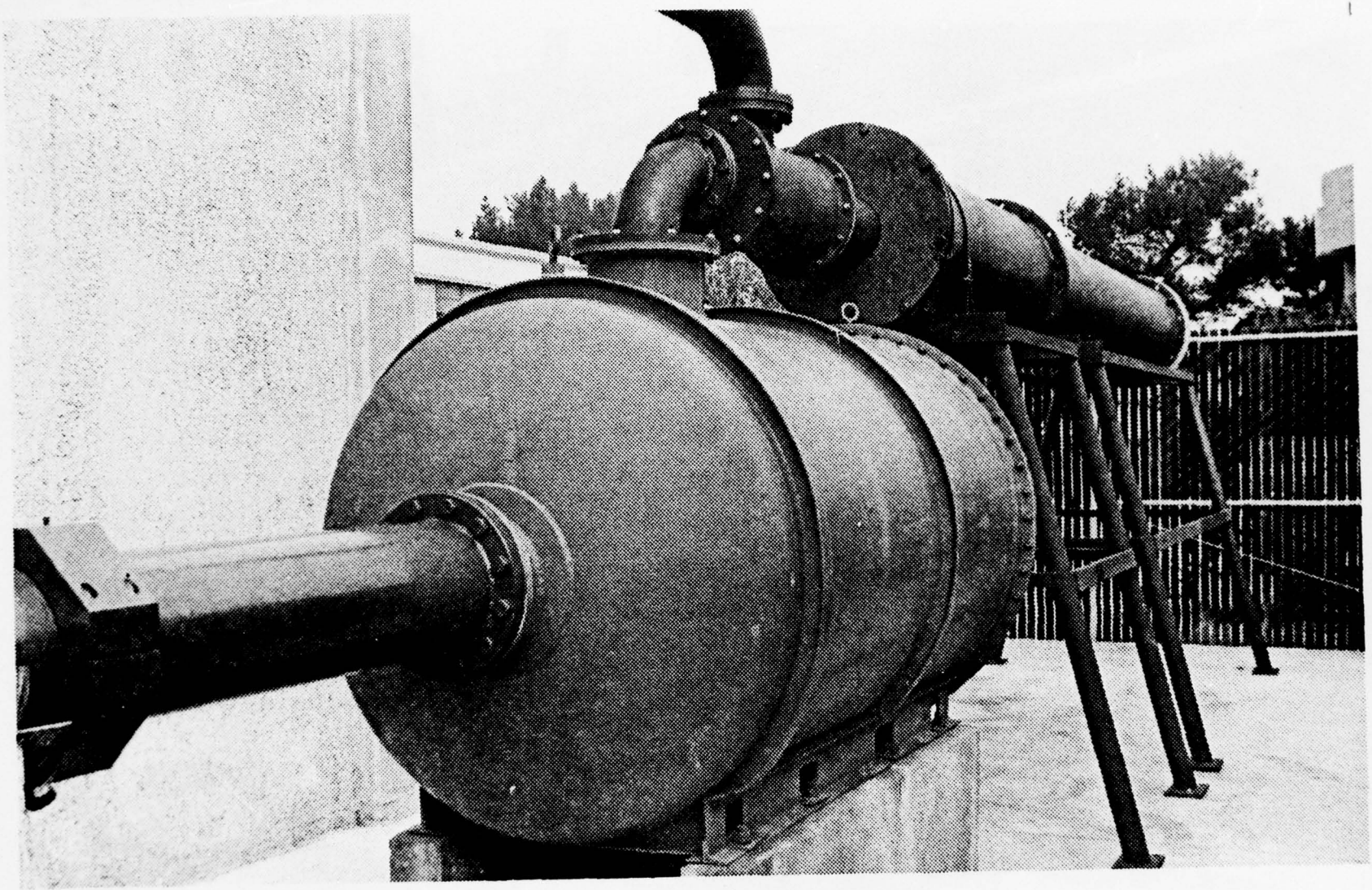


Fig. 19. Photograph of Noise Suppressor

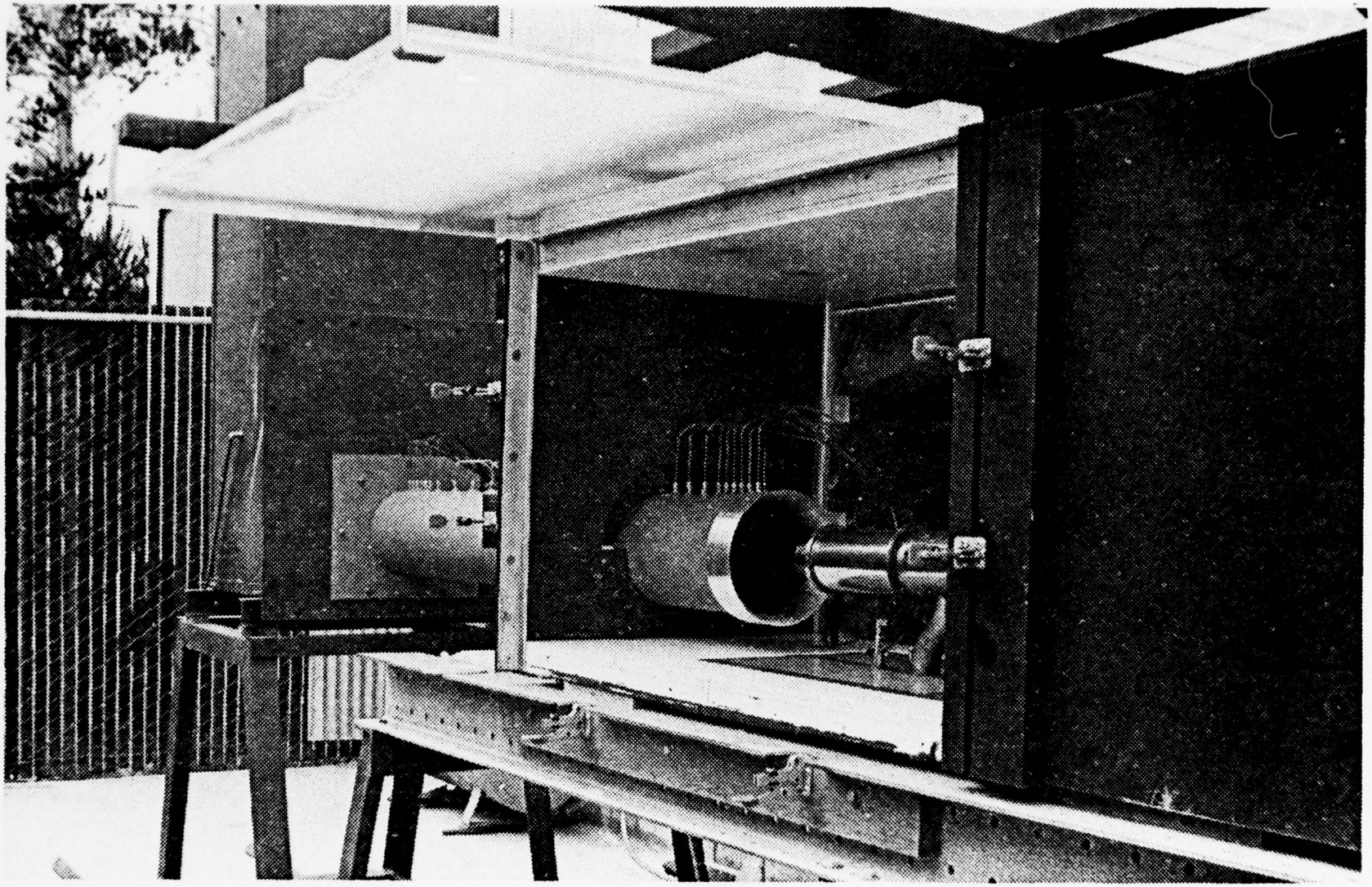


Fig. 20. Modified Test Section

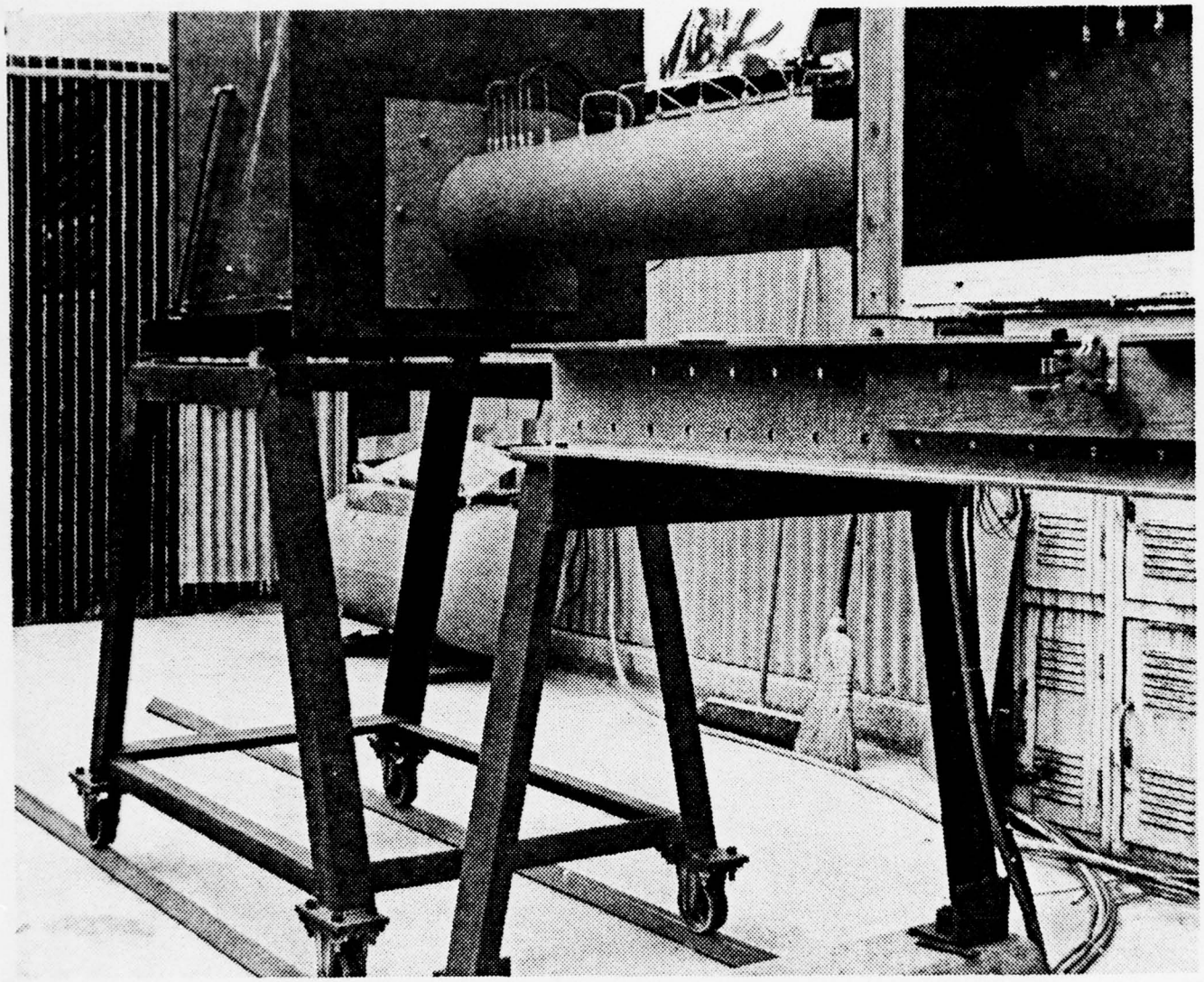


Fig. 21. Modified Stack Translation Apparatus

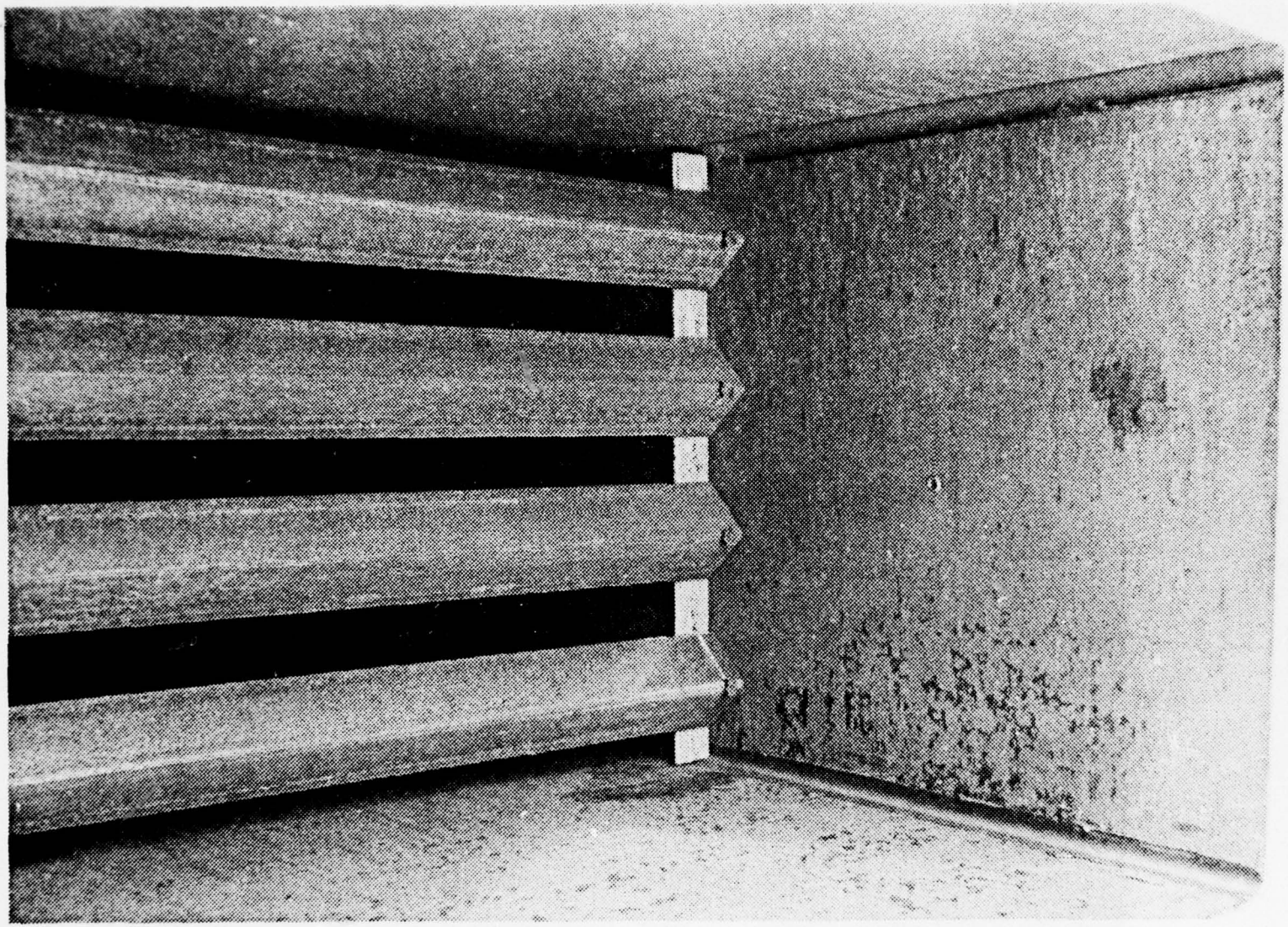


Fig. 22. Grating for Stack Flow Resistance

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